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Groundwater and Nearshore Hyposaline Conditions at Fanning Island during a Period of Higher than Normal Rainfall[1]

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ABSTRACT: Exceptionally high rainfall levels accompanying instability of the Intertropical Convergence Zone in 1972 greatly expanded the freshwater realm on Fanning Island. Changes in the head of the groundwater body (a Ghyben-Herzberg aquifer), as measured at frequent intervals in 11 wells, revealed variations in sediment permeabilities but proved an unsuccessful technique for determining amounts of freshwater discharge into inlets along the lagoon shore. The aquifer was found to store freshwater and then maintain reduced salinities in the inlets long after an initial salinity depression during a period of precipitation. The spatial and temporal distribution of salinities in the inlets closely resembled those of an estuary. However, the factors contributing to salinity fluctuations in each inlet are sufficiently complex and show both regular and irregular patterns of temporal variation, so that the inlets constitute highly unpredictable environments. The biological implications of this unpredictability are deemed interesting because of the close proximity to the predictable and reasonably stable environments of the shallow-water lagoon reefs.

THE MAJOR ATOLLS of the Line Islands are located in the central Pacific between 2° and 6° north latitude. Mean annual rainfall in this region of the Pacific increases northward from the equator, reaching a maximum at the Intertropical Convergence (ITC), which at this longitude normally lies between 5° and 8° N (Seelye 1950). The position and extent of the ITC varies seasonally; it is generally farthest north during the months of September through November and farthest south from April through June. These periods thus correspond to the dry and wet seasons of the Line Islands. Differences in mean annual rainfall among the atolls of Christmas, Fanning, and Washington are nearly as great as the seasonal differences in rainfall received by any one of the atolls (New Zealand Meteorological Service 1956).

The normal seasonal pattern of rainfall is interrupted irregularly by an interval of abnormally high rainfall producing maximum monthly rains in December through March (Doberitz, Flohn, and Schutte 1967). These periods of exceptionally high rainfall correspond with El Niño of the eastern central Pacific and are imposed upon the annual cycle so that the normal wet season may also show above normal rainfall (R. Taylor, personal communication). Beginning in May 1972, rainfall in the Line Islands was measured at near and above record levels. Christmas Atoll, normally the driest of the four major atolls, experienced the greatest above-normal deviations in rainfall of the Line Island atolls over the next 9 months.

In an earlier paper (Guinther 1971), I described the occurrence of estuarine conditions in shallow arms of Fanning Island Lagoon as I had observed them in January 1970. The present paper extends those observations to cover the period of heavy rains in July and August 1972 during the second Fanning Island expedition.

A PROBLEM OF DEFINITIONS

Seawater dilution along a shoreline can occur in a wide variety of situations not readily encompassed in a definition designating a particular type of environment (Day 1951, Caspers 1967,

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Pritchard 1967). Consequently, despite similarities in one aspect or another, few generalizations can be made concerning the ecology of brackish waters. At one end of the spectrum are those physiographic features widely accepted as befitting the term estuaries: the mouths of rivers entering a tidal sea. At the other extreme are freshwater springs which discharge directly into offshore marine waters as described by Kohout and Kolipinski (1967) in Florida. A central problem in "estuarine ecology" is that of deciding where in the spectrum of brackish waters the term "estuary" should be used.

The origin of all freshwater eventually producing a salinity depression in the marine environment (or combining with saline water to produce a brackish water environment) is ultimately some form of condensation from the atmosphere. The importance of the hydrologic cycle notwithstanding, it is the focus at a specific point along the coastline of water precipitated over some wider area that is of primary interest to the aquatic biologist. The precipitated water may reside for some period of time in a groundwater body before being discharged into a stream or directly into the marine environment. The absence of aboveground flow in many instances is a consequence of land soils with high porosity relative to the amount of rainfall received. Aboveground flow may be absent even though the amount of rainfall precipitated on the drainage basin is considerable.

The absence of a freshwater surface flow constitutes the primary objection to the use of the descriptive term estuary for brackish bodies of water on atolls. However, this objection must apply along any coast where significant stream flow into the ocean is intermittent. The statement of Caspers (1967) that "estuaries are limited to river mouths..." is unnecessarily restrictive if one accepts the usual definition of a river as a "stream of water larger than a brook or creek" (*Webster's New Collegiate Dictionary* [1960]). A broader definition of an estuary has been given by Pritchard (1967): "An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage." This definition might also encompass the central lagoon at Fanning. Although a differentiation between estuaries and lagoons has been provided by Caspers (1967): "Estuaries, in contrast to lagoons, are characterized by poikilohalinity and the instability of environmental factors," precise definitions of "poikilohalinity" and "instability" must still be agreed upon to clarify the distinction.

A practical reason for excluding inlets and coastal ponds on atolls from inclusion within the term lagoon is the confusion arising from the presence of a perfectly respectable lagoon as a dominant feature on most atolls. Environments on Diego Garcia Atoll (Indian Ocean), similar in many respects to the inlets described on Fanning (Guinther 1971), have been referred to as "barachois" by Stoddart and Taylor (1971).

With the exception that rivers are absent on low coral islands (although short, intermittently flowing streams may be present), most definitions of estuaries can apply to the inlets at Fanning Island for durations of days to perhaps months. However, these bodies of water rapidly become hypersaline or "inverse estuaries" (Pritchard 1952) when evaporation exceeds precipitation.

Because the tendency in the literature is to restrict the term estuary as has Caspers (1967), I define the brackish-water bodies of water on Fanning Island as "inlets," if a free connection with the lagoon or ocean is present, and "ponds," if no free connection exists. My use of the term inlet is thus comparable to "barachois" of Stoddart and Taylor (1971). The terms inlet or pond refer to geomorphological features and imply nothing about either the hydrology or chemistry, which may differ from atoll to atoll. I demonstrate in this paper that the inlets at Fanning Island behave as estuaries under conditions where precipitation exceeds evaporation.

THE GHYBEN-HERZBERG LENS

The low-salinity, groundwater body of porous islands is of the Ghyben-Herzberg type. The relationships between precipitation, island size, permeability, and porosity of soils, and the formation and maintenance of a basal groundwater-body have been discussed by Cox (1951) in reference to coral islands and by Wentworth (1947) in reference to high volcanic islands.

The formation of a body of freshwater within the porous structure of an island is the result of the downward percolation of water derived from precipitation and the relative inhibition of mixing processes (such as diffusion and turbulent water movement) by the island sediments. The lower density of freshwater as compared with the density of seawater causes freshwater to float on, or displace, seawater within the island sediments. The difference in density between fresh and normal seawater is such that for every unit of freshwater floating above sea level, there must be a corresponding 40 units of freshwater displacing seawater below sea level. For brackish water the expected depth of the lens below sea level would decrease as the difference in salt content between the brackish and sea water decreased. A sharp boundary between fresh water and seawater is seldom maintained in the groundwater body, the lens being progressively saltier with depth; precise determination of the depth of the body is thus nonsimple on theoretical grounds.

For the purpose of discussion I assume an island without a fresh groundwater body and with sediments of equal porosity throughout. An evenly distributed addition of freshwater by precipitation over this island will result initially in the formation of a downward percolating body of freshwater. This freshwater body will encounter seawater at sea level, and, while density adjustments (vertical adjustments) occur, some freshwater near the shoreline will be lost by outward (lateral) flow. The remaining fresh water, or at least that excess not removed from the groundwater by plants or by evaporation, can only be lost by lateral flow toward the shoreline. Because all of the water lost from the groundwater body by lateral flow must flow through the island margins, while only that water falling on the center of the island must flow through the inland portions of the island, an even flow can be maintained only if the hydraulic gradients determining the rate of flow are steeper near the shoreline (Cox 1951). The hydraulic gradient is the change in head (elevation of the freshwater level above sea level) per unit distance measured in the direction of flow. The resultant shape of the head is thus convex upward in cross section, highest at the center of the island, and curving steeply downward at the margins. Although some of the fresh water remains above sea level, the majority of it (40 units of depth for every unit of head) will reside below sea level. The base of the groundwater body, that portion below sea level, will be convex downward, so that the overall form is lenticular in cross section.

An adjusted Ghyben-Herzberg lens can constitute a vast storage reservoir of fresh water on low, coral islands, because the great bulk of the groundwater is found below sea level. The actual size of the aquifer and the salinity of the water within it will vary with time in response to the long and short term inputs of rainwater. In addition, the depth of the lens and its salinity at any given point will bear a relationship to the island size and shape, the porosity and permeability of the sediments, and the tidal range. Tidal fluctuations are transmitted through the lens and contribute to the mixing of fresh with salt water as the interface between them moves up and down through the sediments. Damping of these fluctuations and hence reduction of tidal mixing increases with decreased sediment permeability and distance inland from the shore. Small islands of high permeability may not maintain a freshwater lens long after a period of precipitation.

An island with a freshwater aquifer will discharge fresh or brackish water along its margins as long as the lens maintains a head above sea level. Without additional input the lens will become progressively more brackish, decrease in size, and eventually disappear altogether. Were this to occur, the groundwater would be as saline as the ocean water.

The inlets of the lagoon increase the linear extent of the island margin and also serve to focus fresh or brackish water discharge from the aquifer at specific points along the lagoon margin. Salinities in the inlets are reduced immediately during precipitation on their surface waters, but salinity reduction can continue for some period thereafter by discharge of water from the aquifer. Relative to the volume of the receiving water the inlets are surrounded by a greater length of aquifer margin than is the lagoon proper.

METHODS

Salinity reduction in the inlets is not entirely a direct one resulting from precipitation falling on the inlet waters, but is also related to various properties of the island aquifer. For this reason a study of the extent of and changes in the aquifer at Fanning Island was undertaken during the 1972 Fanning Island Expedition. Shallow wells were constructed in the vicinities of the Cable Station Inlet and the Napu Naiaroa Inlet (Figs. 1–3) and water levels in the wells followed intermittently during July and August 1972. All wells were dug by hand to a decimeter or more below the water table and the hole encased with asbestos pipe (Transite). A cover was placed over the pipe opening to reduce evaporation. The elevation of a mark on the upper lip of each casing was determined in relation to a United States Coast and Geodetic Survey (USCGS) bench mark at the cable station and to an arbitrary fixed point at Napu Naiaroa with a Path automatic level. Water levels in the wells were recorded as the distance from the casing lip to the water surface as measured by a meter rule. Later, these data were transformed by adjustments to the common fixed point at each locality. The results of three, nearly continuous surveys of water levels, each spanning a complete tidal cycle, are presented in Figs. 4–6.

Elevations of the casing lip, ground elevations around the well, and lower end of the casing (the depth from which water in the well was drawn) are given in Table 1.

Rainfall amounts were recorded daily at the cable station and these data are given in Table 2 for the period covering the expedition's visit. The rain gauge was read each morning and these measurements are arranged with the 24-hour total given for the day and following night of the listed date. Individual rain squalls during the continuous survey periods are indicated by the letter "P" at the top of Figs. 4 and 5. No precipitation occurred during the 26-hour survey at Napu Naiaroa. A temporary rain gauge was installed at Napu Naiaroa for 11 days in August.

Tidal changes in the lagoon were measured continuously by two float-type gauges, one located at the end of the lagoon pier near Cable Station Estuary and the other located on the bridge over Napu Naiaroa Estuary. The latter gauge was in place for only 6 days. The tide records were related to the fixed points at each locale, although this determination was less accurate than that giving the well elevations. The tide records in Figs. 4, 5, and 6 are shown as wide bands reflecting this uncertainty. Matching the tidal curve to the fixed point required measuring the water level while concomitantly marking the tide trace on the recorder. The position of the tide record in Figs. 4 and 5 is based on two estimates which differed from each other by 0.006 meter. The tide curve is drawn as the shaded area between these two estimates. Five estimates relating the tide curve to the fixed point at Napu Naiaroa were made. One of these was made on 10 August and is shown in Fig. 6 (labeled TM). Relative to this estimate, the other four estimates have the following deviations: estimate 2, -0.025 meter; estimate 3, $+0.009$ meter; estimate 4, -0.024 meter; estimate 5, $+0.066$ meter. The shaded tidal curve in Fig. 6 is drawn with the upper edge at estimate 1, judged as the best estimate because of its close correspondence with the water level at station 6 at the following high tide (deviation of the station 6 reading from estimate 1 at 2100, 10 August is -0.001 meter). The lower edge of the tidal curve represents the median between estimates 1 and 2 and encompasses the mean of the estimates after discarding estimate 5. Water levels in the inlets were measured either with a meter rule from a mark on a span above the station (stations 5 and 10 at cable station) or with a meter rule affixed to a stake (station 6 at Napu Naiaroa).

Elevations at Cable Station Inlet were adjusted to mean lower low water (MLLW) in the lagoon from the reported elevation of bench mark no. 1 at 8.55 feet (2.606 meters). Bench mark no. 2 could not be located but repeated surveys relating bench mark no. 1 to bench mark no. 3 revealed the latter (mounted on an iron pipe) to be 6 mm lower than the reported elevation of 3.23 feet (0.985 meter). The reported datum (MLLW) is approximately 36 cm below the lowest low water recorded on the lagoon tide gauge at the cable station during the period of our stay.

The difference between MLLW in March 1967, when the elevations of the USCGS bench marks were established relative to the lagoon

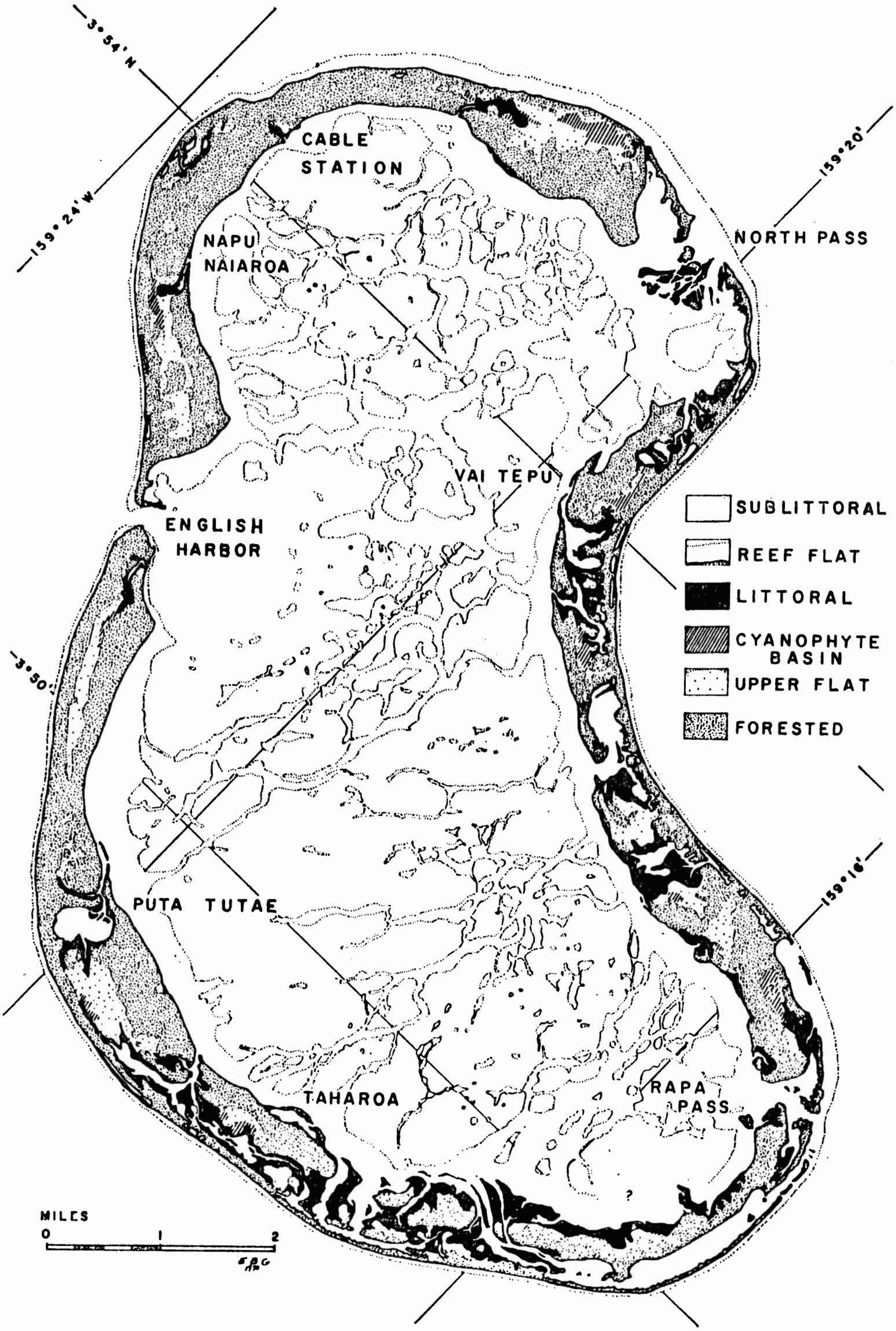

FIG. 1. Fanning Island showing the location of the two inlets studied.

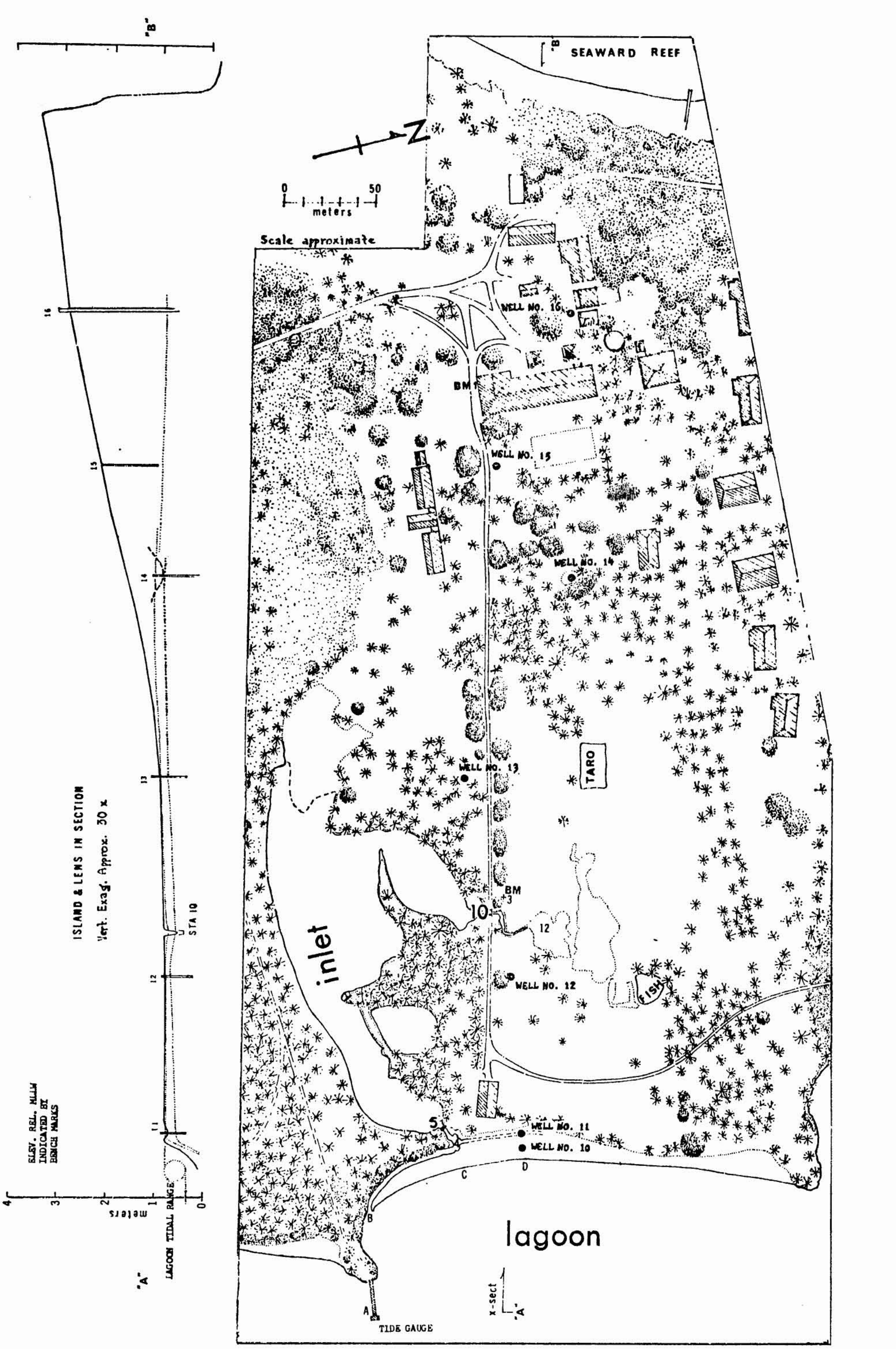

FIG. 2. The inlet at the cable station and the cable station grounds showing sampling sites and well locations. Sampling stations on the inlet are indicated by numbers; those on the lagoon shore by letters. Map based on ground survey and aerial photographs. Dotted lines in the sectional drawing beside map are the upper and lower elevations of the water table observed during the study.

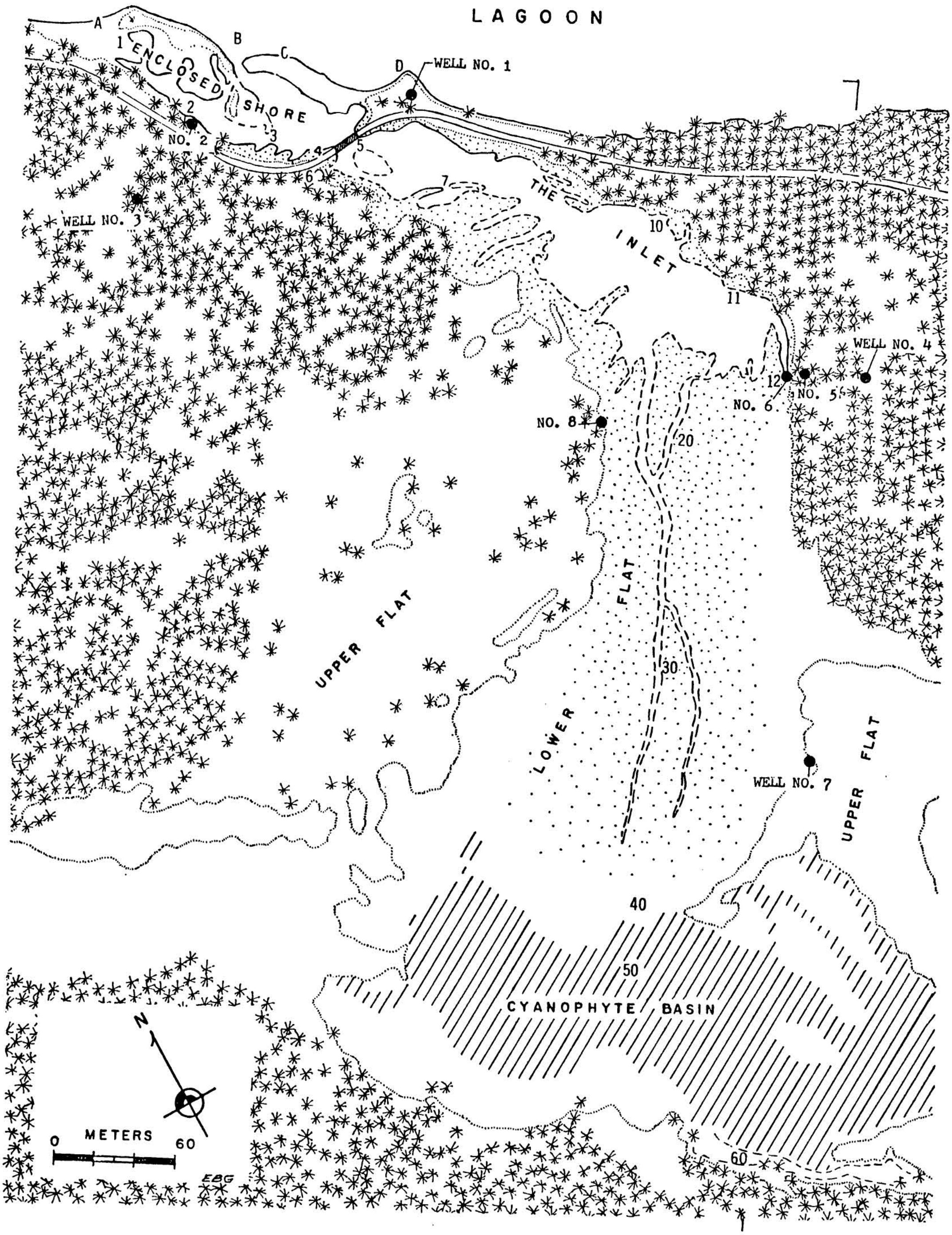

FIG. 3. The inlet at Napu Naiaroa showing sampling sites and well locations. Sampling stations indicated by numbers or letters. Map based on ground survey and aerial photographs.

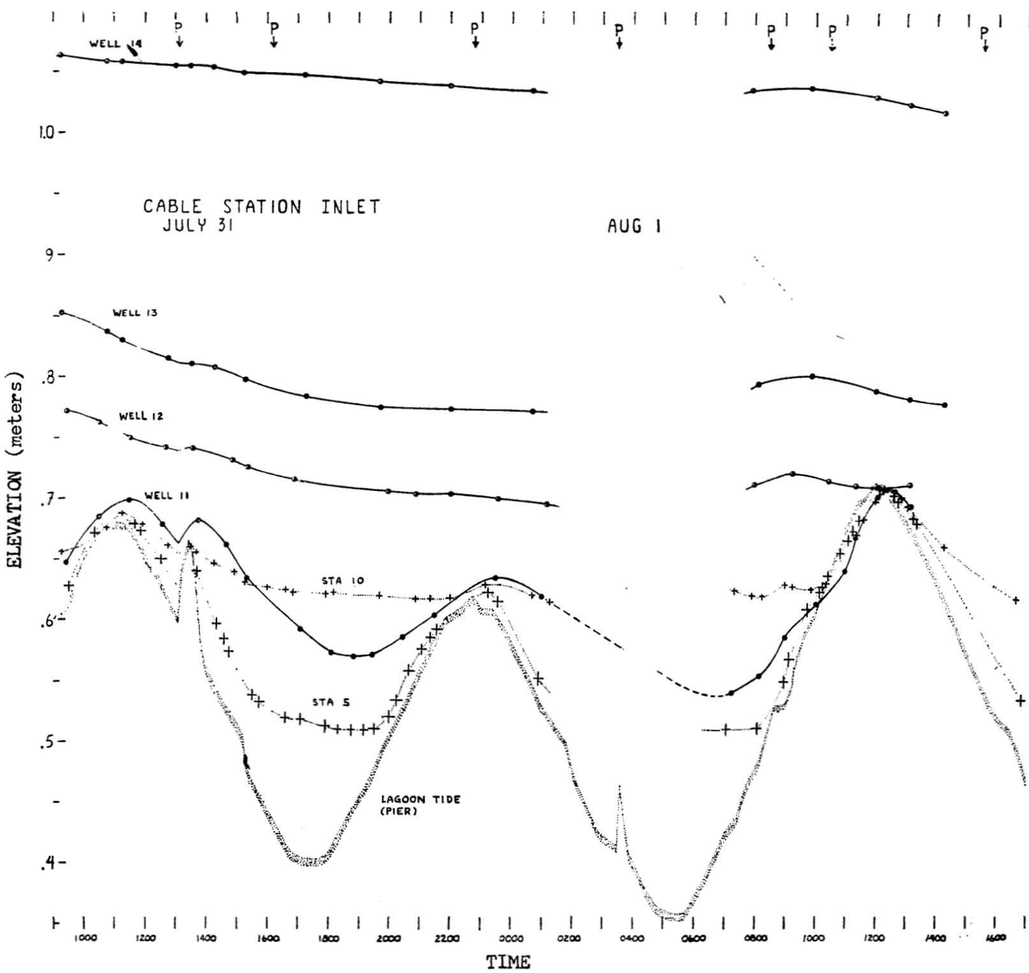

FIG. 4. Water level changes in wells and in the inlet at the cable station on 31 July and 1 August 1972. Tidal curve shown as a stippled line. The occurrence of rain squalls is indicated by the letter P along the upper margin.

and lower low water (LLW) in the summer of 1972 is probably due to a real difference in sea level. Fanning Island is located just south of the equatorial countercurrent and sea level fluctuates seasonally. Exceptional positive deviations occur when transport by the countercurrent is strong as would be indicated by the occurrence of El Niño in the eastern equatorial Pacific during the latter half of 1972 (Wyrtki 1973). A decrease in the mean water level of the lagoon of over 30 cm was noted between December 1972 and April 1973 by Dr. James Jones (personal communication).

I have attempted to relate the elevations at Napu Naiaroa to those at the cable station by comparing the tide records made simultaneously at these locations. The tide at Napu Naiaroa has an amplitude which is approximately 80 percent that of the lagoon tide at the cable station. In addition, the Napu Naiaroa tide lagged behind the cable station tide by some 20 to 60 minutes. The shallow reef flat fronting Napu Naiaroa and the narrow entrance into the enclosed shore of Napu Naiaroa Inlet may be responsible for these differences. Separate regressions of the nine high tides and the 10 low tides recorded simultaneously at Napu Naiaroa and the cable station between 10 August and 14 August were made.

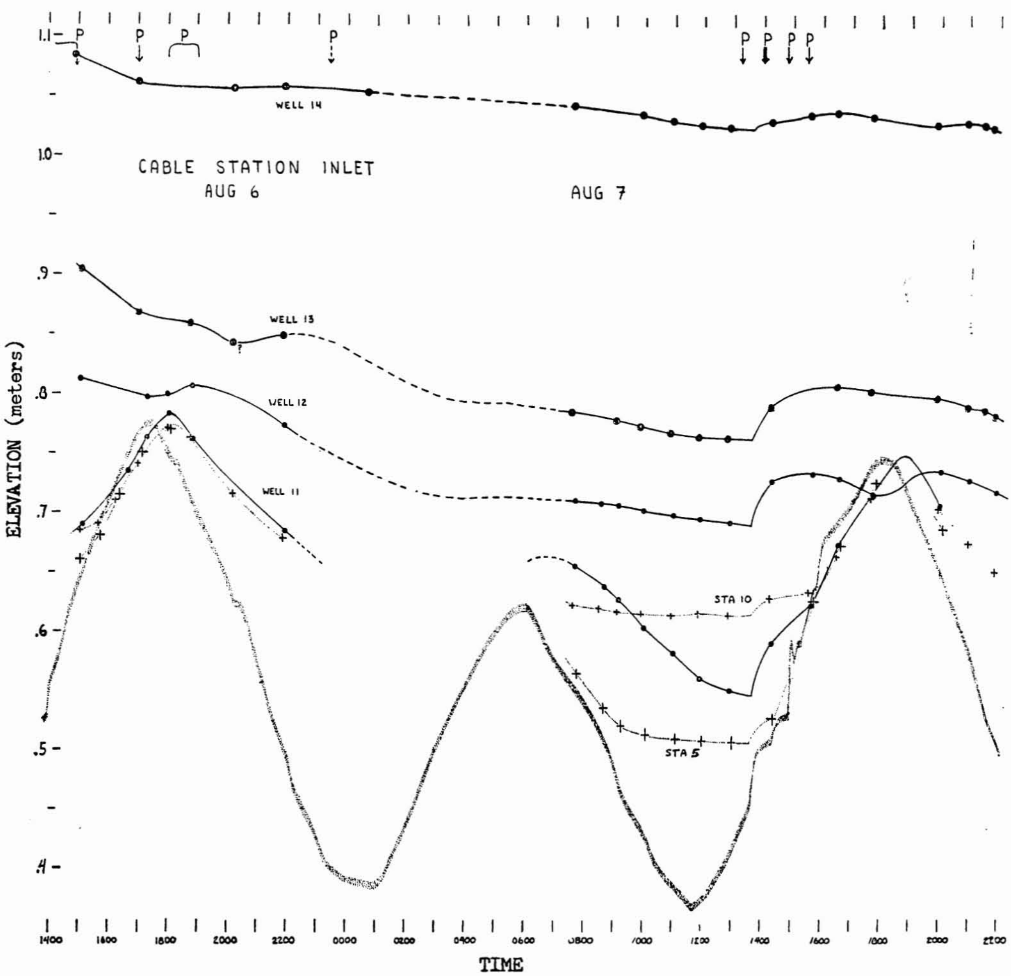

FIG. 5. Water level changes in wells and in the inlet at the cable station on 6 and 7 August 1972.

The linear regression of the nine high tide levels at Napu Naiaroa upon the same tidal points at the cable station gave the best fit (correlation coefficient = 0.986, as compared with 0.847 for the low water points) as might be expected because high water would be least affected by restrictions on water flow at Napu Naiaroa. Surprisingly, however, the linear regression of all 19 (high and low water) tidal points at Napu Naiaroa on the same tidal points at the cable station gave an even better fit (correlation coefficient = 0.997) and the regression equation: sea level at Napu Naiaroa = 0.80 (sea level at the cable station) − 0.194 meters.

The absence of a one-to-one unit correspondence between water levels at these two locations is an expression of the tidal damping observed at Napu Naiaroa, but creates problems in attempting to relate elevations at Napu Naiaroa to the bench marks at the cable station. It seems unjustified to add 0.194 meters to the arbitrary fixed point at Napu Naiaroa (and hence to all elevations at Napu Naiaroa) since it can never be true that: elevations at Napu Naiaroa = 0.80 (elevations at the cable station). In terms of groundwater levels, an absolute correspondence at mean sea level would be more meaningful than a correspondence at MLLW (which is $x = 0$, $y = 0$ in the regression equations above).

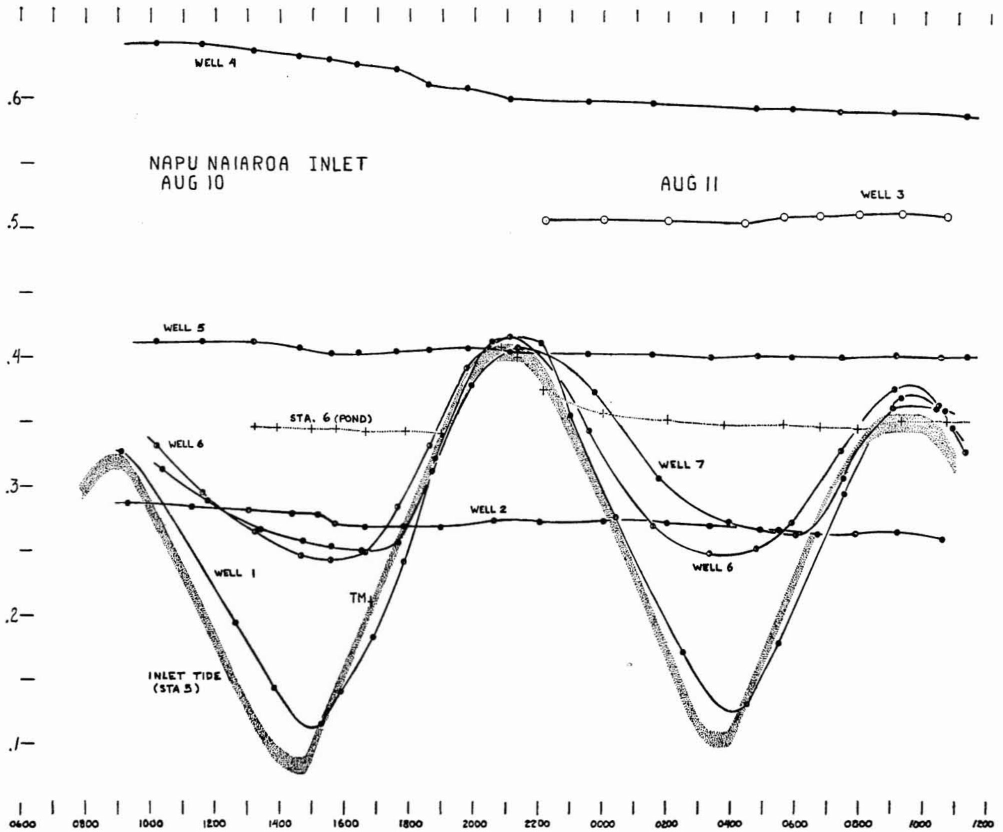

FIG. 6. Water level changes in wells and in the inlet at Napu Naiaroa on 10 and 11 August 1972. Base point of elevation scale is arbitrary and not the same as that used for Figs. 4 and 5 (see text).

GROUNDWATER OBSERVATIONS

The description of a Ghyben-Herzberg lens presented earlier was greatly simplified to facilitate understanding of the general principles involved. In particular, island sediments were assumed to be homogeneous. Although it is likely that the island on which both the cable station and Napu Naiaroa are located (Fig. 1) holds one large aquifer, this aquifer shows variation in response to vertical tidal fluctuations and horizontal flow from place to place. Such variation indicates heterogeneities in the permeabilities of the island sediments. Three types of wells can be differentiated on the basis of tidal damping:

TYPE 1—Characterized by well no. 1, the lens shows only slight tidal damping with a time lag on the order of 30 minutes. The small tidal damping indicates sediment of relatively high permeability.

TYPE 2—Characterized by moderate tidal damping expressed particularly by a reluctance to follow the tidal lows. Time lag is greater for tidal lows than for highs. Wells located on the lagoon beach (well no. 11) or on the inlet flat (well no's 6 and 7) illustrate this pattern. Essentially the same pattern is shown by the open inlet stations (stations 5 and 10 at the cable station and station 6 at Napu Naiaroa). The aquifer is apparently shallow at these well sites and salinity fluctuations may be great.

TYPE 3—Wells in which the tidal amplitude is highly damped. Tidal lag increases with distance from the shoreline. Well no. 2 is particularly

TABLE 1

ELEVATIONS OF WELLS AND FIXED POINTS ON FANNING ISLAND

LOCATION	ELEVATION (METERS) CASING TOP	GROUND	DRAW POINT
Napu Naiaroa*			
Bridge Abutment (NE)	1.000	–	–
Well No. 1	0.819	0.45	–0.28
Well No. 2	0.716	0.52	
Well No. 3	0.834	0.73	
Well No. 4	1.055	0.96	0.48
Well No. 5	0.766	0.58	0.07
Well No. 6	0.454	0.26	–0.06
Well No. 7	0.426	0.27	0.01
Cable Station†			
Bench Mark No. 1	2.606	–	
Bench Mark N. 3‡	0.979	0.8	
Well No. 11	0.851	0.74	0.32
Well No. 12	0.876	0.80	
Well No. 13	1.238	1.01	
Well No. 14	1.141	0.92	
Station 5 (Mark on Bridge Curb)	1.038	0.37§	
Station 10 (Mark on Bridge Curb)	1.001	0.47§	

* Elevations at Napu Naiaroa relative to an arbitrary elevation of 1.000 on bridge abutment.

† Elevations at the cable station relative to United States Coast and Geodetic Survey bench mark no. 1, reported elevation 8.55 ft relative to the MLLW of the lagoon (taken as 2.606 m here) and 8.36 ft relative to the MLLW on the ocean.

‡ United States Coast and Geodetic Survey bench mark no. 3 reported at 3.23 ft MLLW lagoon and 3.04 ft MLLW ocean. Elevation given above is based on our survey and is relative to MLLW lagoon as determined from bench mark no. 1.

§ Elevation of inlet bottom.

interesting. A type 1 or 2 response might be expected because this well is located within 1 meter of the inlet shore. The small tidal amplitude shown by this well is a function of low-permeability sediments, particularly in the deeper regions through which tidal fluctuations are transmitted. Note that the tidal effect on the level of water in well no. 12 is very noticeable on 6–7 August when the tidal range in the lagoon is great and not so noticeable on 31 July–1 August when the lagoon tidal range is smaller.

In accordance with Ghyben-Herzberg theory, the wells show a progressive increase in head with increasing distance from the shore. A cross section of the island (A–A′) and aquifer at the cable station grounds is included in Fig. 2. The ground surface is the upper solid line (and the dashed line at well no. 14 to the north of the transect). The two dotted lines represent the upper and lower limits reached by the groundwater during the course of this study as measured at each of the wells. Well no. 14 appears to be near the region of maximum head. Well no. 15 was excavated to a depth of over 1 meter below the ground surface without penetrating the aquifer. Well no. 16 is the old freshwater well for the cable station and the distance from its lip to the water surface (over 2 meters) made monitoring of level changes difficult.

The aquifer is close to the surface in the lagoonward portion of the transect, and is periodically exposed in depressions over the lower ground to the north of the transect. The Gilbertese natives on Fanning take advantage of the close proximity of the aquifer to the surface in such areas to construct taro patches and freshwater fishponds. The low ground between these features at the cable station was flooded throughout the period of this study. The presence of flooded ground does not necessarily

TABLE 2

24-HOUR RAINFALL TOTALS MEASURED BEFORE 0800 ON THE CABLE STATION GROUNDS

JULY	RAINFALL (cm)	AUGUST	RAINFALL (cm)
9	0.28	1	0.56
10	1.17	2	0.99
11	0.33	3	0.00
12	0.91	4	0.23
13	0.00	5	2.01
14	0.00	6	6.88
15	0.00	7	0.71
16	0.51	8	0.00
17	0.96	9	1.60 (1.83)
18	2.92	10	0.00 (0.00)
19	0.00	11	0.18 (0.13)
20	0.91	12	0.00 (0.00)
21	0.18	13	0.68 (0.25)
22	0.68	14	0.00 (0.00)
23	0.86	15	0.00 (0.00)
24	0.23	16	0.00 (0.00)
25	0.48	17	0.00 (0.00)
26	0.00	18	2.56 (2.49)
27	2.67	19	3.76 (3.68)
28	2.90	20	0.18
29	1.12	21	3.66
30	6.73	22	0.00
31	0.91	23	0.13

NOTE: 24-hour total is the amount of rain recorded between 0800 on the date given and 0800 the next day; values given in parentheses were recorded near the tide gauge at Napu Naiaroa.

indicate a low permeability of the soils. Rather, the lens itself "breaks the surface" in these areas and is contained by the surrounding higher ground. A slow but constant flow drains the flat into the estuary through a narrow stream (station 10). Thus the configuration of the ground at the cable station allows the inlet to intercept a large portion of the aquifer head adjacent to it and the inlet maintains a low salinity. The narrow entrance connecting the Cable Station Inlet to the lagoon and the overall shallow depth of this inlet further contribute to the low salinity by restricting tidal exchange.

Rain squalls approached the study sites from the southwest, passing first over the lagoon. Each squall was accompanied by a seiche which was recorded on the tide record. A rain squall usually produced an immediate rise in the level of water in every well; the magnitude of this rise involves consideration of the amount of rain falling, the duration of the rainfall, and the carrying capacity (porosity) of the upper sediments. The amount of precipitation in individual squalls was not recorded, and cannot be related to the increase in head without some estimate of the actual volume of water represented by a particular increase. Very rough estimates of the water volumes involved may be gleaned from the data obtained at the Napu Naiaroa Village well and well no's 12 and 13 at Cable Station Inlet. The level in the village well rose approximately 15 cm on 19 August, following a rainy period which precipitated 3.7 cm of water. These numbers indicate that the porosity of the upper soils is about 25 percent. This estimate is probably high since the input was spread over most of the day and some loss in head by lateral and particularly by vertical flow was occurring. On 7 August, the rainfall over a 2-hour period measured at the cable station was 0.7 cm. The rise in water levels at well no's 12 and 13, if the loss rate that was occurring prior to the input period is taken into account, amounts to about 5 cm. These values give an estimate of the porosity of 14 percent.

If we compare the increase in water level of each well following a particular squall, we see that the increase is greatest near the lagoon margin and decreases inland. (Note: well no. 11 responds additionally to the seiches.) Whether this decrease in response inland is the result of changing porosities (capacities of the soil to hold water) or shoreward flow of the rainfall excess is not clear. Those wells closest to the shoreline also lost water more rapidly after the rain ceased.

The course of water level changes in the wells at Napu Naiaroa during a 26-hour survey on 10–11 August (Fig. 6) was uncomplicated by pulses of freshwater input (rain squalls). For each well at Napu Naiaroa the mean water level between 0900 on 10 August and 1000 on 11 August was calculated by reading the respective curves at 63 consecutive points (every 12 minutes). These data are given in Table 3.

Note that the mean water level at well no. 1 is below that at well no. 2, although the latter is closer to the shoreline. Well no. 1 is located on a spit of land that probably was built up from sediments derived from the lagoon reef (mostly sand). The narrowness of the spit also imposes

TABLE 3

MEAN WATER LEVELS IN THE WELLS AT NAPU NAIAROA BETWEEN 0900 ON 10 AUGUST AND 1000 ON 11 AUGUST

SITE	MEAN WATER LEVEL*
Inlet (Sta. 5)†	0.253
Well No. 1	0.257
Well No. 2	0.272
Well No. 4	0.611
Well No. 5	0.406
Well No. 6	0.312
Well No. 7	0.312

* In meters, based on arbitrary base point elevation.
† Based on estimate 1 (TM—see Fig. 6); see text.

limits on the size and depth of the aquifer. Well no. 2, on the other hand, is located in a region where at least the upper sediments are derived from the inlet and adjacent coconut grove. Mention has already been made of the differences in tidal responses between these two wells.

Well no. 6 and well no. 7 are both located at the same elevation on the lower flat of Napu Naiaroa Inlet. Although well no. 7 is located nearly 200 meters farther up the inlet and its tidal curve correspondingly lags behind that of well no. 6, the mean water level in these two wells was identical during the 25-hour period. This result may be partly coincidental, since water in well no. 7 does not reach as low a level as that in well no. 6 (see Fig. 6), but the close correspondence of the water in these two wells over a tidal cycle may indicate a homogeneous geomorphology of the lower flat. Salinities in well no. 7 were lower than those at well no. 6 during the survey period.

The recording tide gauge was moved from Napu Naiaroa Inlet (station 5) to the drinking-water well at the nearby village for the period from 14 to 21 August. The continuous trace obtained shows a progressive decrease in the head of the freshwater aquifer until 19 August when rainfall again raised the aquifer head. (The village, occupied on a temporary basis, was not in use at this time.) The rates of head change for four consecutive 24-hour periods beginning at midnight on 14–15 August were: -0.027, -0.034, -0.040, and -0.024 meters/24 hours. The apparent decrease in loss rate during the fourth 24-hour period is in part the result of recharge (0.9 cm precipitation measured at Napu Naiarao) on the afternoon of the 18 August. Using the estimate of porosity of 25 percent calculated previously for this location, we see that the rainfall input could have increased the head by 0.036 meter, giving a corrected change in head of -0.060 meter over 24 hours.

The discharge of fresh water to the shore involved in the head changes calculated above could be determined only if the porosity of the sediments, the contribution of increasing displacements of salt water by fresh water (vertical flow), and the loss of groundwater by transpiration were known. Porosity is likely to vary from place to place, so that the pattern of water loss per unit area per unit time could be quite different from the pattern of head change per unit time as indicated by any particular series of wells. A more accurate estimate of fresh water discharge into the inlets could be obtained from water volume transports through the narrow entrances to the inlets, if measured over several tidal cycles. A limited number of such measurements was made at both Napu Naiaroa and the cable stations inlets and will be reported on in a later paper.

Water in the inland wells remained fresh (refractive index = 1.3330) during the course of this study. On the other hand, salinities varied in wells close to shore. The ranges recorded on 10 and 11 August at Napu Naiaroa are given in Table 4. No consistent pattern related to the tide curve emerges from the time course of these variations. Salinities were not always higher on the 11th compared with those on the 10th. Salinities in these wells were within the ranges given when subsequent measurements were made on 13, 18, 19, and 20 August. Well no. 1 may be an exception; although the salinity was not measured following approximately 1 week of very little rain, the water in this well was brackish enough on 17 August to be undrinkable.

At the cable station, refractive indices exceeded 1.3330 only in well no. 11 (1.3330–1.3332; 0‰–1‰ salinity) and well no. 10 (1.3334–1.3349; 2‰–10‰). Well no. 10 was dug into the beach slope in front of well no. 11 to sample groundwater salinities at the shoreline. Lagoon salinities just offshore of well

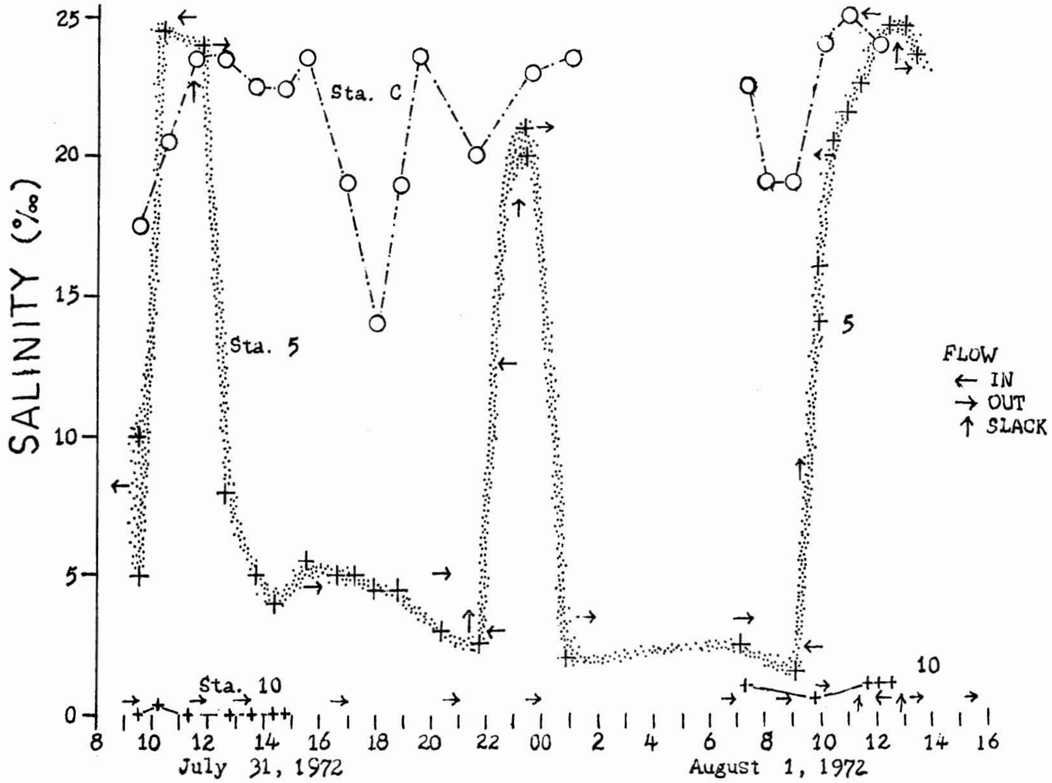

FIG. 7. Salinity changes along the lagoon shore (station C) and at two inlet locations (stations 5 and 10) on Cable Station Inlet on 31 July and 1 August 1972. Direction of water flow at the two inlet stations is indicated by the small arrows.

TABLE 4

RANGES IN SALINITY RECORDED AT NAPU NAIAROA WELLS, 10–11 AUGUST 1972

WELL NO.	REFRACTIVE INDEX	SALINITY "PARTS PER THOUSAND"
1	1.3330–1.3332	0–1
2	1.3330–1.3333	0–2
6	1.3359–1.3364	16–18
7	1.3336–1.3337	3–4
8	1.3359–1.3373	16–23

no. 10 varied between 16‰ and 26‰ (refractive indices = 1.3359–1.3380) during this period. These three sampling sites illustrate the steep salinity gradient which existed over a few meters of lagoon beach in August 1972.

OBSERVATIONS ON THE INLETS

Water levels and salinities at selected open-water stations were measured during the course of the three extended surveys at Napu Naiaroa and Cable Station Inlets. Water levels were measured at three stations (two at the cable station and one at Napu Naiaroa) in addition to the records provided by the tide gauges. These data appear in Figs. 4–6. The locations of all sampling stations on the inlets and lagoon shore are indicated on Figs. 2–3. Water-level changes at the three stations studied were similar to those described for the type 2 wells. High tides lagged behind those of the lagoon and the lag time increased upstream. Low water was higher than low water in the lagoon and appeared independent of the lagoon tide. Station 6 at Napu Naiaroa was a pond separated from the inlet by

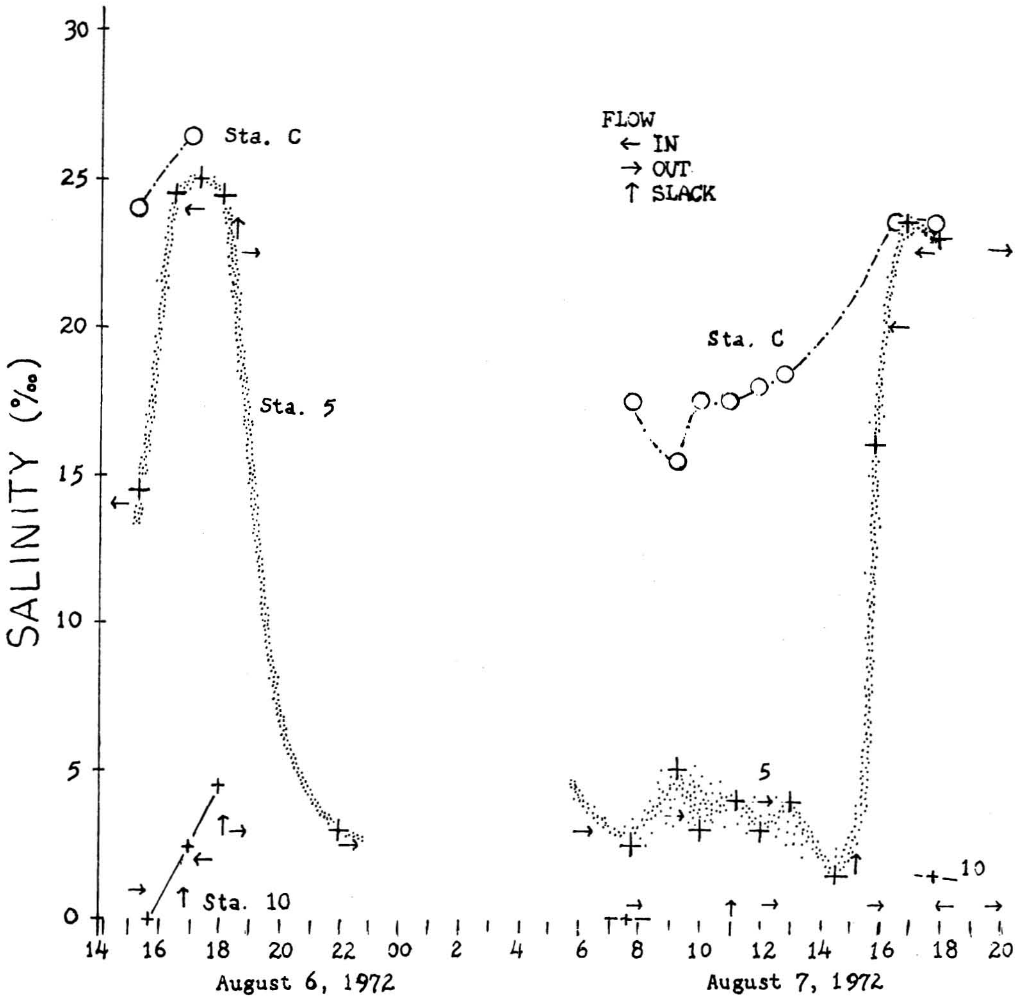

FIG. 8. Salinity changes on 6 and 7 August at Cable Station Inlet.

a sill at approximately 0.35 meter (relative to the arbitrary fixed point). The independent (lower) level reached by the water in this pond may have been close to that of the surrounding water table. Salinities in the pond on 10 August were between 5‰ and 6‰ (refractive indices = 1.3339–1.3340) until 1900 hours when water flooded the pond on the rising tide and raised the salinity to 18‰. The lower high water (LHW) on 10 August did not introduce inlet water into the pond, nor would have the high tides on 9 August. The LHW on 11 August, while adding some water to the pond, did not alter the salinity from 18‰. Salinities at station 6 fluctuate in response to direct precipitation and tidal additions, but the water level in the pond could be maintained against the hydraulic gradient at low tide only if relatively impermeable sediments surrounded and lay beneath this site. The absence of tidal fluctuations in nearby well no. 2 further suggests that this area is underlain by sediments of low permeability, and these sediments must extend well into the region of the Ghyben-Herzberg lens. Sediments near the inlet shore are fine, almost claylike, and contain considerable organic matter derived from the nearby coconut grove.

The water at station 5 and station 10 (Cable Station Inlet) is not separated from the lagoon by a sill, although the hydraulic gradient between these stations and the lagoon is small when the distances involved are considered. Water flowed out of the estuary during the entire time the level of water at these stations was at the low plateau, and the restriction of this flow at low tide maintained the head. In fact, outflow at station 5 continued for 2 hours after the water level began to rise with the tide. At station 10 on 31 July, flow was always outward; and inward flow on 1 August lasted for less than 2 hours (Fig. 7). During periods of heavy input to the aquifer, station 10 is functionally a stream feeding water intercepted by the low ground to the north of station 10 into Cable Station Inlet. Salinities given in Figs. 7 and 8 show that the water in Cable Station Inlet was mostly derived from land drainage. Lagoon water appears briefly at station 5 with each flooding tide.

Another feature at Cable Station Inlet serves to focus fresh water lost from the lens through the inlet. On the lagoon beach, between the beach berm and the vegetation line, there is a shallow depression which slopes to the south. Well no. 11 is located in this depression. As the groundwater body within the beach rises with the tide, the aquifer head "surfaces" in the depression and fresh water flows into the channel of Cable Station Inlet just below station 5.

ECOLOGICAL SIGNIFICANCE OF SALINITY CHANGES: CONCLUSIONS

The primary determinant of salinities in any given body of water at Fanning Island is the relationship between precipitation and evaporation that exists and has existed earlier over some period of time. The balance between these two factors is more or less the same over the entire atoll at any one time, and three additional factors contribute to salinity variations that are seen from place to place: (1) the degree of restriction of seawater flow into the body of water; (2) the area of the drainage basin and tidal flats relative to the volume of the pond or inlet; and (3) the relationships between aquifer, permeability of sediments, and the configuration of the body of water. Isolated ponds may be exposed extensions of the groundwater body and reflect the salinity of the groundwater in their vicinity.

The 1972 visit of the University of Hawaii expedition to Fanning Island coincided with the early months of an exceptionally high rainfall period that lasted through the first quarter of 1973. During the period of observations the extent of fresh water in the groundwater body must have been near maximum. Mean salinities in open bodies of water, including the lagoon (see Smith and Pesret 1974), were greatly reduced from the values observed in January 1970 (see Gordon and Schiesser 1970). Flooding of low ground was common in 1972, promoted both by the high rainfall and the high sea level which accompanies the rainfall anomaly (Wyrtki 1973). The observations reported herein thus represent conditions near the low-salinity extreme for Fanning Island.

Napu Naiaroa Inlet is typical of the larger inlets scattered about the atoll in the size and depth of the inlet itself and in the extent of its associated tidal and supratidal flats. Daily salinity variations at Napu Naiaroa are the result of several factors including precipitation, evaporation, and tidal currents. However, precise measurements of these factors over several days, combined with an understanding of the hydrodynamics of the inlet, would not permit a prediction of salinity changes without knowledge of the conditions over some indefinite period prior to the observations. A brief, heavy rainfall, isolated in time, will drastically affect salinities in the inlet for only a few days at most. Several tidal flushings return salinities to those of the lagoon, but the extremes in salinity that occur between the high and low tides during the period of readjustment depend on the conditions of the aquifer and the salinity of the lagoon fronting the inlet (in addition to the amount of fresh water precipitated). The condition of the aquifer is dependent upon the amount and distribution in time of rainfall over a period of several weeks, while the salinity of the lagoon reflects the balance between precipitation and evaporation over many months. Fluctuations in mean sea level change the dynamics of both the aquifer and of tidal exchange between the inlet and the lagoon. Salinities in the inlet thus result from complex interactions between factors with daily, monthly, seasonal, and even longer patterns of variation. The physical characterization of each inlet must be based on consideration of these island-wide factors in

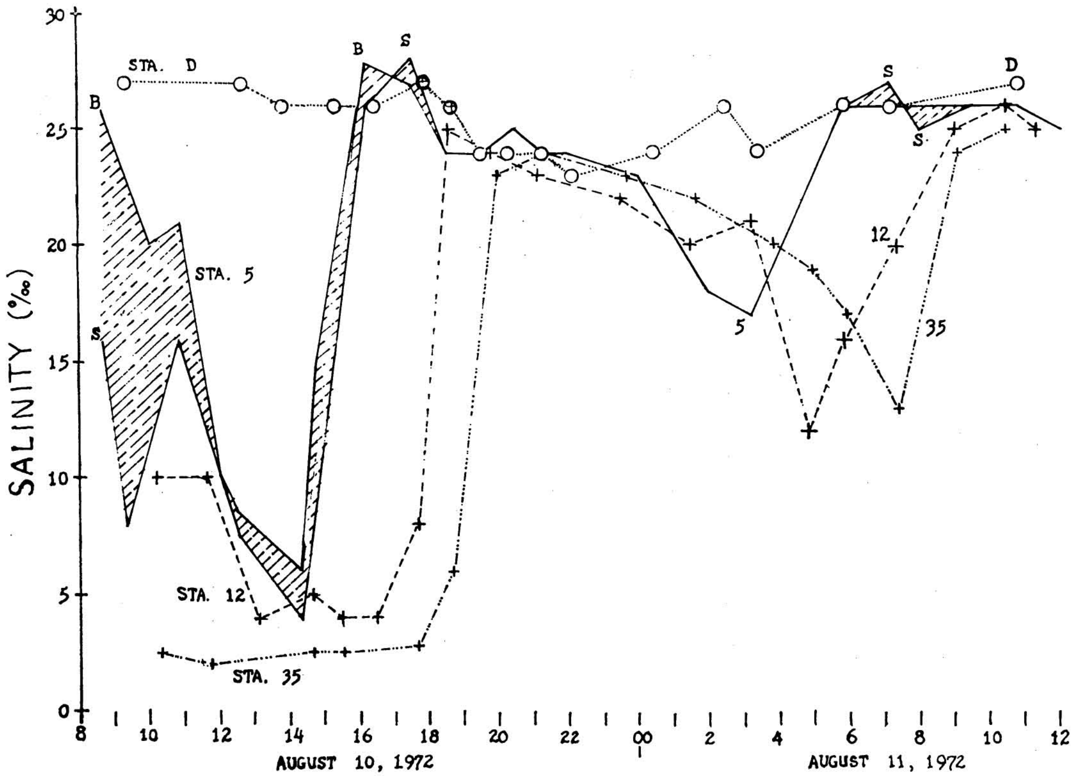

FIG. 9. Salinity changes along the lagoon shore (station D) and at three inlet locations (stations 5, 12, and 35) in Napu Naiaroa Inlet on 10 and 11 August 1972. At station 5, two samples were taken, one at the surface (S) and one approximately 1 meter deeper (B).

addition to the three factors of local features listed previously.

The result of climatic changes having seasonal or longer periodicities is that the dominance of salinity regimes is shifted in the inlets and ponds; that is, fresh water may predominate for some period of time and then, as a result of a change in climatic factors, hypersalinity may predominate. These shifts are accompanied by changes in conditions in the groundwater and the lagoon, so that the terrestrial and marine environments are also affected to some degree. At Fanning, the enclosed and semienclosed, shallow-water environments undergo regular, although somewhat unpredictable, changes in physiography. The far reaches of the inlets in January 1970 were inhabited almost solely by mats of blue-green algae (Guinther 1971). These mats were present in August 1972 but were modified in color and form, reflecting a shift in the dominant species (or perhaps the physiology of the same species) of cyanophytes. Typically freshwater invertebrates (larvae of *Odonata* and Chironomidae) were present, in addition to the ubiquitous land crabs (*Cardisoma carnifex*) and euryhaline fishes (*Chanos chanos* and *Tilapia mossambica*).

Fanning Island is a moderately "wet" island with a mean annual rainfall of 206 cm (New Zealand Meteorological Service 1956). Salinities in the ponds and inlets seldom reach upper extremes that might exclude life. However, the fluctuations in salinity that occur are unpredictable in a biological sense (see Slobodkin and Sanders 1969). In this respect the inlets differ from many "true" estuaries having relatively constant sources of fresh and salt water (i.e., a river and the open ocean). In these estuaries the range and duration of salinity fluctuations at any given place are reasonably predictable from time to time. Even if the amplitude of the fluctuation varies, its periodicity is closely linked to the tidal cycle; and organisms inhabiting these regions have behavioral or physiological mechanisms that enable them to survive in the fluctuating environment. Successful colonization in an unpredictable environment can occur only if the species is eurytopic or if colonizers are available when conditions to which the species is adapted appear. The duration of each salinity regime relative to the life cycles of potential stenotopic colonizers becomes an important aspect of the problem of colonization. Thus, the lack of predictability of salinity fluctuations may contribute as much to species distributions in the inlets at Fanning as does the range of these fluctuations.

The wide variety of hydrologic features at Fanning provide refuges for stenohaline species, regardless of the conditions predominating at any one time. In January 1970, bodies of water could be found that were nearly fresh (6‰ salinity) while other locations experienced hypersalinity (up to 42‰). In August 1972, hypersaline environments could not be found, but the various bodies of water displayed salinities from essentially fresh water to normal seawater.

The occurrence of highly unpredictable environments adjacent to relatively benign and predictable environments (the tropical, shallow-marine environments of the lagoon and ocean reef flat) is of experimental interest regarding questions on the relationship between species diversity and environmental stability (see Sanders 1968, Slobodkin and Sanders 1969). The experimental value of the inlets is further enhanced by the fact that shifts in salinity regimes occur on a time scale that allows colonization by stenotopic organisms.

SUMMARY

1. Instability in the Intertropical Convergence Zone during the latter half of 1972 resulted in above normal amounts of precipitation at Fanning Island, Line Islands.
2. The high level of rainfall received by the island produced extreme conditions of hyposalinity in inlets and ponds. The groundwater body (a Ghyben-Herzberg aquifer) was expanded and may have reached maximum capacity by July 1972.
3. The response of the groundwater body to recharge and the effect of tides on the aquifer were studied in wells by frequently measuring the groundwater head. These studies revealed differences in sediment permeabilities and pointed out the difficulty of determining aquifer discharge to the shore from changes in the elevation of the water table.
4. The inlets—shallow arms of the lagoon—became brackish or freshwater environments during periods of heavy precipitation. Discharge from the aquifer maintained lowered salinities in the inlets long after precipitation had ceased. The spatial and temporal distribution of salinities in the inlets closely resembled those of an estuary.
5. Although precipitation, predominating over evaporation during the study period, tended to lower salinities in the lagoon as a unit, the inlets "focused" loss of fresh water from the aquifer at specific points along the shoreline.
6. Salinity variation in the inlets was deemed highly unpredictable, as such variation is dependent upon the long- and short-term balance between precipitation and evaporation, tidal parameters, and the mean level of the sea. These parameters show both regular and irregular patterns of variation at Fanning.
7. The degree of response to any combination of the above parameters varied from inlet to inlet owing to differences in tidal exchange between inlet and lagoon and differences in the configuration of each inlet relative to the aquifer.
8. It was hypothesized that the unpredictability of the inlet environments with reference to salinity contributes to the distribution, in space and time, of organisms inhabiting these bodies of water and the shallow reef flats of the lagoon shore.

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